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RSRE
MEMORANDUM No. 3670

ROYAL SIGNALS & RADAR ESTABLISHMENT

A COMPACT FREQUENCY-STABLE PULSED CO_2 LASER

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MINISTRY OF DEFENCE,
RSRE MALVERN,
WORCS.

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Date: March 1984

SUMMARY

The aim of this memorandum is to outline the results of work carried out at RSRE to develop a compact frequency-stable CO_2 laser. This work has resulted in the production of a simple, highly compact device (165 x 80 x 50 mm) having a 1.5 MW, 35 ns output pulse which is both inter and intra-pulse frequency-stable to within 3 MHz.

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RSRE MEMORANDUM

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D L Jordan, R C Hollins

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1 INTRODUCTION

Existing direct detection pulsed CO_2 laser rangefinders exploit the high output power, short pulse duration and ruggedness of compact TEA lasers. The technology of such devices is well developed and they can be purchased from British industry. For typical output powers (1-2 MW) and weather conditions, the range is limited to ~ 5 km. For various applications such as ground to air and naval use, somewhat longer ranges (~ 12 km) are required. Coherent detection offers a possible route to obtaining the required range enhancement whilst still maintaining a compact laser.

In order that the heterodyne beat signal can be detected within a narrow frequency bandwidth, with consequent low noise levels, frequency stability is required in both the pulsed laser transmitter and the C/W local oscillator reference source. The laser pulse length required depends upon the envisaged application. For rangefinding, the short cavity TEA laser described in this memorandum is undoubtedly the best option, having the shortest pulse length (35 ns), the highest peak power, the widest tuning range and being the simplest and most compact of all the frequency stable laser options. In situations where extremely acccurate doppler information is required, hybrid lasers having a pulse length of ~ 2 μs would be preferred. Between these two extremes, a whole range of device options, including an extended pulse-length version of the laser described here, is possible. These other options will be described in a future memorandum. Irrespective of which type of laser is required, it is necessary in a narrowband system to operate on a single transverse and axial mode, and also to keep the mode frequency constant to within a few MHz, the actual stability required depending upon the application.

2 SHORT CAVITY LASER

The 10.6 μm (28 THz) P(20) transition in the 10.6 μm band (00°1-10°0), on which TEA lasers which do not contain a line selecting element oscillate, has a gain - bandwidth of ~ 4.5 GHz at one atmosphere. A conceptually simple technique of ensuring single axial mode operation is to make the laser resonator sufficiently short that when one axial mode is at the centre of the gain curve, the others are sufficiently well separated in frequency that they are below threshold.

We have carried out measurements on two different length UV-pre-ionised TEA lasers[1]. Both devices used a transverse discharge of area 115 x 20 mm^2 across an 11 mm gap between Rogowski-profiled electrodes. The discharges were driven from a 30 kV, 10 nF storage capacitor via a peaking capacitor. A one atmosphere gas mix (CO_2:N_2:He = 2:1:2) was used. The cavity lengths of the two lasers were 165 mm and 225 mm. In each case a plane - plane resonator with an 85% reflectivity output mirror was used, and the fully reflecting mirror was mounted on a piezoelectric length transducer to allow the longitudinal modes to be finely tuned across the gain curve of the medium. An intracavity iris was used to define the resonator radius. Figure 1 shows a picture of the smaller laser; it was built around a 165 x 80 x 50 mm envelope of ultra-low-expansion silica for thermal stability. Both lasers invariably operated on the P(20) line without any attempt at line control.

The axial mode structure of the lasers was analysed by observing the beat notes of the modes of the TEA laser (much attenuated) with a stable C/W laser using a sensitive wide bandwidth HgCdTe detector. Besides the beat note corresponding to the major TEA laser axial mode, a weak secondary mode is usually detectable in the Fourier transform of the heterodyne signal (Figure 2). The relative amplitudes of the competing modes can be measured at each frequency of operation from the Fourier transforms and a set of results for the 165 mm laser is shown in Figure 3. The results given in this figure show a large pulse-to-pulse scatter in the mode ratios; this is due to statistical fluctuations in the number of photons (~ 5) in the two modes at lasing threshold. In the presence of severe fluctuations in relative mode intensity, a narrowband laser radar transmitter, which is required to emit most of its output energy in a mode of known frequency, must be designed to achieve a high average mode intensity ratio (say 100:1). If this is not done, then a considerable proportion of the pulses of the laser will display little power on the desired mode and this, in a radar system, greatly increases the probability of missed signals. However, if the laser is sufficiently short an average mode intensity ratio of 100:1 is readily achievable; Figure 3 shows that the average mode intensity ratio, which is the square of the amplitude ratio, for the short laser is greater than 100:1 even for a frequency offset of the principal mode from line centre of 300 MHz, corresponding to a third of the axial mode spacing. The need for a high average mode intensity ratio does however limit the length scalability of this type of laser, unless the added complexity of an injection locked system in which the TEA laser is locked to a frequency stable injection source is used. Hollins and Jordan[2] have shown that the gain-switched spike mode intensity ratio (I_1/I_2) scales with laser length L as

$$\frac{I_1}{I_2} \propto \exp\left(\frac{A}{L^2}\right) \qquad (1)$$

where A is a slowly varying function of the other parameters; the output energy scales with L. These considerations lead to a maximum-usable laser length (whilst still keeping $I_1/I_2 > 100:1$) of ~ 26 cm.

All TEA lasers used in direct detection systems use an intracavity 8.5 mm diameter iris to give what is generally referred to as a single transverse mode (TEM_{00}) output. In fact they do not, a typical photon drag recording from a 225 mm single axial mode TEA laser containing an 8.5 mm diameter iris is shown in Figure 4. A pronounced modulation of ~ 20 MHz in the output pulse due to the mode beating between the TEM_{00} mode and a higher order TEM_{10} mode[3] is seen, the effect being most pronounced in the tail of the pulse. There is, in fact, a wide range of aperture diameters (6-8.5 mm for the short laser, 7-8.5 mm for the longer laser) for which transverse mode beating was not detectable even using heterodyne detection during the gain-switched spike, but readily observable in the tail of the pulse. However, for rangefinding applications the gain-switched spike is the only part of the output pulse of interest, and so it is only necessary to design the laser to be single transverse mode in the spike. Hollins and Jordan[2] show that the transverse mode intensity ratio scales according to

$$\frac{I_1}{I_2} \propto \exp\left(\frac{B}{a^2}\right) \tag{2}$$

where B is a slowly varying function of the laser parameters. The pulse energy also scales sharply with resonator radius a, principally because the mode area is proportional to a^2.

Combining the scaling laws for both axial and transverse modes indicates that TEA lasers could be scaled to an average mode purity of 100:1 in the gain-switched spike at a cavity length of around 26 cm and an iris diameter of ~ 9 mm; the output energy in the gain-switched spike would be ~ 40 mJ. This is comparable with existing TEA lasers used for direct detection rangefinding.

The actual frequency stability of the laser within a pulse has been measured by mixing its output with a low pressure C/W laser actively stabilised to the centre of the P(20) line. By de-tuning the TEA laser up to 450 MHz from the centre of the gain curve, the frequency within the gain-switched spike was found to be constant to within 3 MHz (measurement limited). However, a nearly parabolic increase in TEA laser frequency with time (chirp) occurs during the tail of the pulse, amounting to ~ 12 MHz over 1.5 µs. This is shown in Figure 5, which shows the beat frequency f as a function of elapsed time from the start of the gain-switched spike (when the frequency is f_o) for a large number of separate pulses using beat frequencies from 10-50 MHz. This is a non-resonant effect independent of the tuning of the laser, and is explained by a model based upon a laser-induced medium perturbation[4]. The solid line is a theoretical curve using the theory of Ref (4). Preferential heating of the gas within the mode volume causes a pressure gradient which forces gas out of this region during the tail of the pulse. The resulting refractive index change causes the frequency chirp; the delay between the gain-switched spike and the onset of the chirp is due to gas kinetics effects. The chirp in the tail of the pulse does not however affect the suitability of the laser for rangefinding applications, which only use the gain-switched spike. A method of eliminating such chirps in pulsed lasers has recently been described by Hollins and Jordan[5].

The pulse-to-pulse frequency stability is also of considerable importance. The random shot-to-shot scatter in the laser gain-switched spike frequency is only of order 1 MHz. Unfortunately this may be superimposed upon an undesirable systematic beat frequency drift. The sources of these drifts are shown in Table I, which is taken from Ref (6). These results were obtained by observing changes in beat frequency over about 100 pulses taken at 30 sec intervals; the laser enclosure was deliberately heated to observe the effects of temperature changes. The best achieved thermal stabilities are +5 MHz/°C using flowing gas and -16 MHz/°C for a sealed device. This performance is limited by expansion of the cavity structure, and also by thermal expansion of the gas in the case of the unsealed devices. These values could be considerably improved, and in theory temperature induced frequency drifts almost eliminated by the judicious use of the correct materials and construction techniques. Any residual drift in the laser frequency can be removed using a simple active stabilisation scheme. Figure 5 shows the measured beat frequency as a function of time for the laser operating at about 0.5 Hz with active stabilisation. Using this system the laser frequency can be confined indefinitely to within ± 2 MHz.

3 CONCLUSIONS

In this memorandum we have described how a compact TEA laser having a suitable pulse length, output energy and frequency stability for pulsed coherent detection may be constructed. It uses existing well developed TEA laser technology and could undoubtedly be readily produced by British industry at very little extra cost than existing compact direct detection lasers. In combination with a small (< 100 mm) frequency stable waveguide local oscillator (the technology of which is also well developed) it would form an extremely powerful and compact rangefinder and would undoubtedly significantly increase the existing direct detection ranging distance.

Although we have not studied the frequency behaviour of high pulse repetition frequency lasers, the technology of highly compact 100 Hz long life sealed-off TEA lasers, which was pioneered in this division[7] is now available in industry. We feel that the marrying of this frequency stable laser work, to the 100 Hz sealed laser work could be readily carried out in industry and should be urgently pursued. We also at present have a world lead in both compact frequency stable lasers and compact sealed high prf devices. The combining of these leads would give the UK a commanding position in this important area.

A future memorandum will deal with the signal processing aspects, including the effects of speckle and multi-pulse averaging of return signals, and give estimates of laser output energies and prf's needed for likely scenarios.

4 ACKNOWLEDGEMENTS

The authors are indebted to P H Cross for designing and building the TEA lasers.

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TABLE I

CAUSES OF FREQUENCY DRIFT IN ATMOSPHERIC-PRESSURE CO_2 TEA LASERS

	Effect	Magnitude of Frequency Drift
1	Changes in Cavity Length	
	Thermal expansion of cavity material:	
	glass	-140 MHz/°C
	ule silica	-0.8 MHz/°C
	expoxies and other incidental materials	-10 MHz/°C
	Thermal expansion of tuning element:	
	bimorph	~100 MHz/°C
	pzt tube	~ 5 MHz/°C
2	Changes in Gas Refractive Index	
	Thermal expansion:	
	Unsealed laser	+20 MHz/°C
	Sealed laser	1 MHz/°C
	Gas composition changes:	
	Leakage of helium	0→ -5 MHz/minute
	Discharge dissociation of CO_2	~ 0.1 MHz/shot

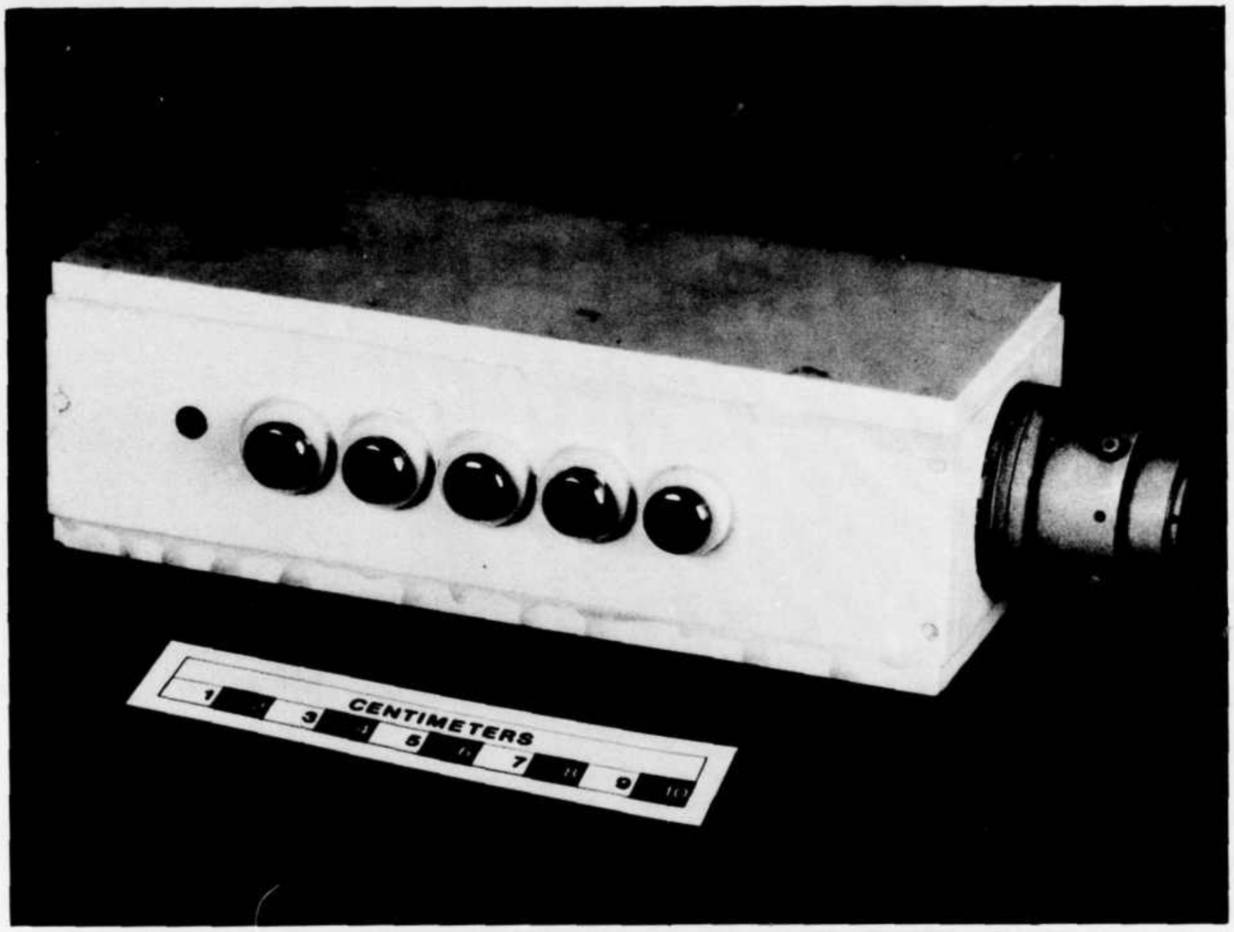

FIG 1

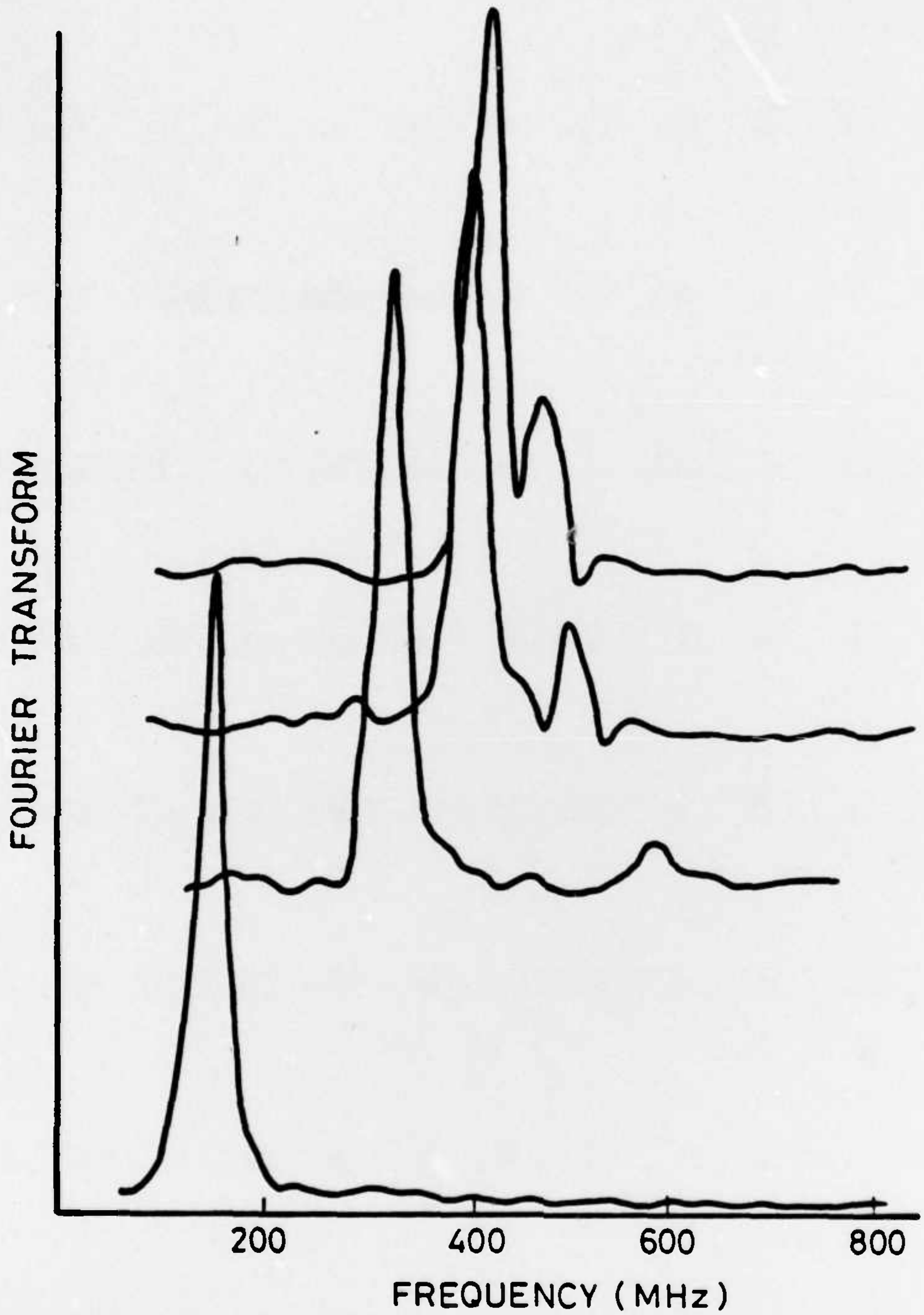

FIG. 2. FOURIER TRANSFORMS OF BEAT NOTES OBTAINED AT DIFFERENT FREQUENCY OFFSETS OF THE PRINCIPAL TEA LASER MODE FROM LINE CENTRE. (CAVITY LENGTH 165mm; LONGITUDINAL MODE SPACING, 909 MHz)

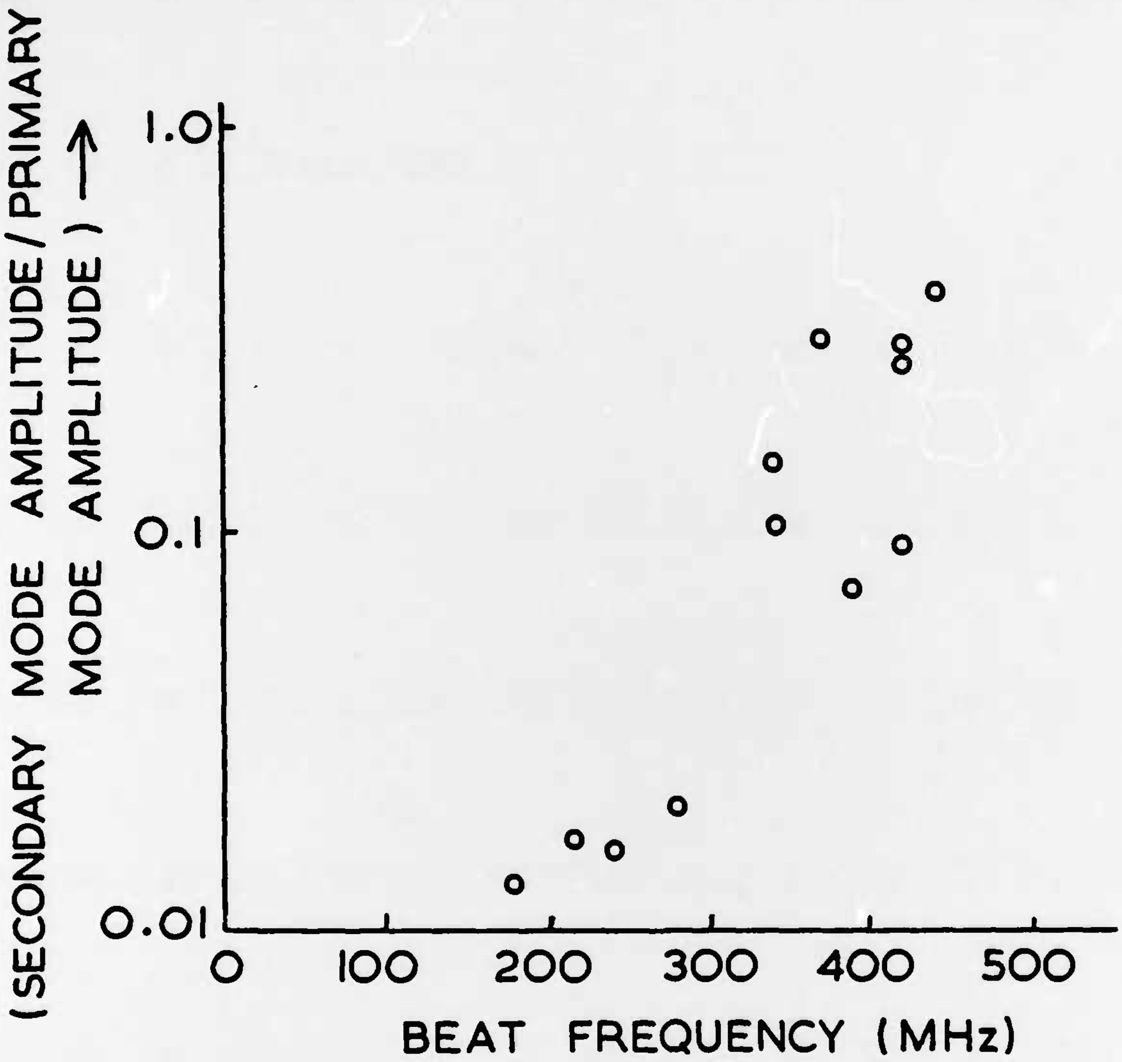

FIG. 3 RELATIVE AMPLITUDES OF PRIMARY AND SECONDARY LONGITUDINAL MODES VERSUS FREQUENCY DISPLACEMENT OF PRIMARY LONGITUDINAL MODE FROM LINE CENTRE.

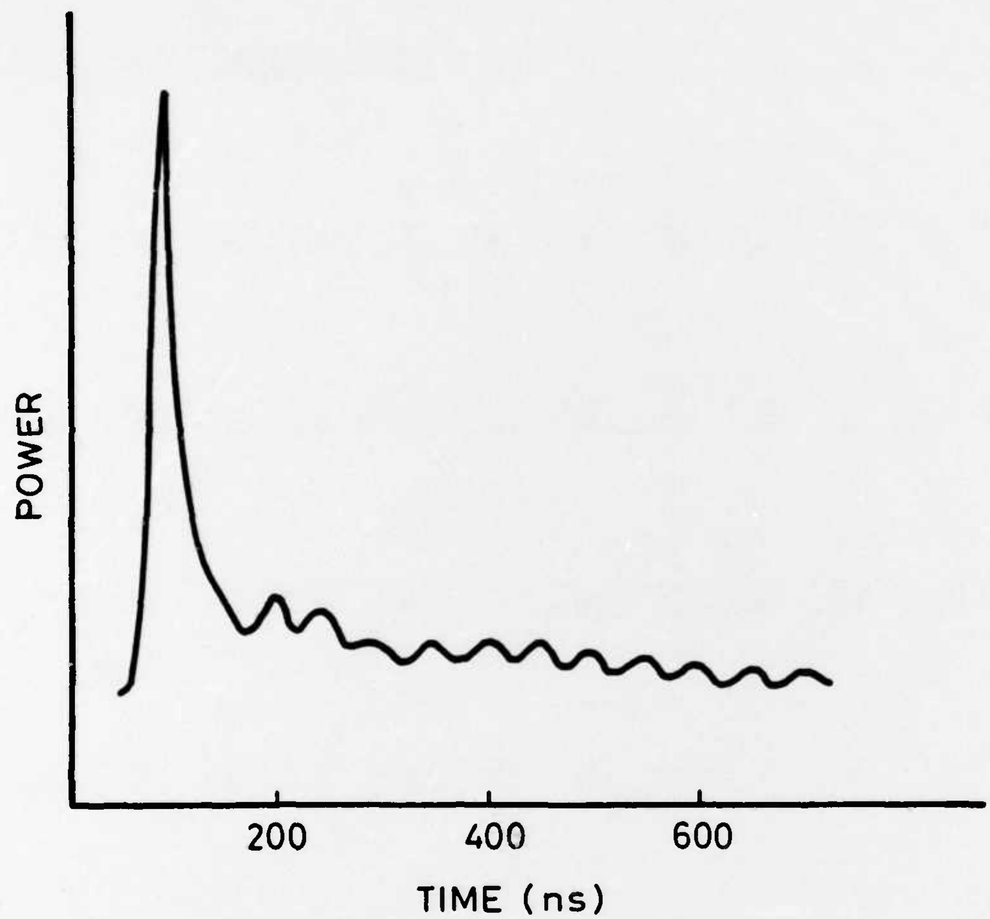

FIG. 4. PHOTON DRAG RECORDING (CAVITY LENGTH, 225mm; IRIS DIAMETER, 8.5mm)

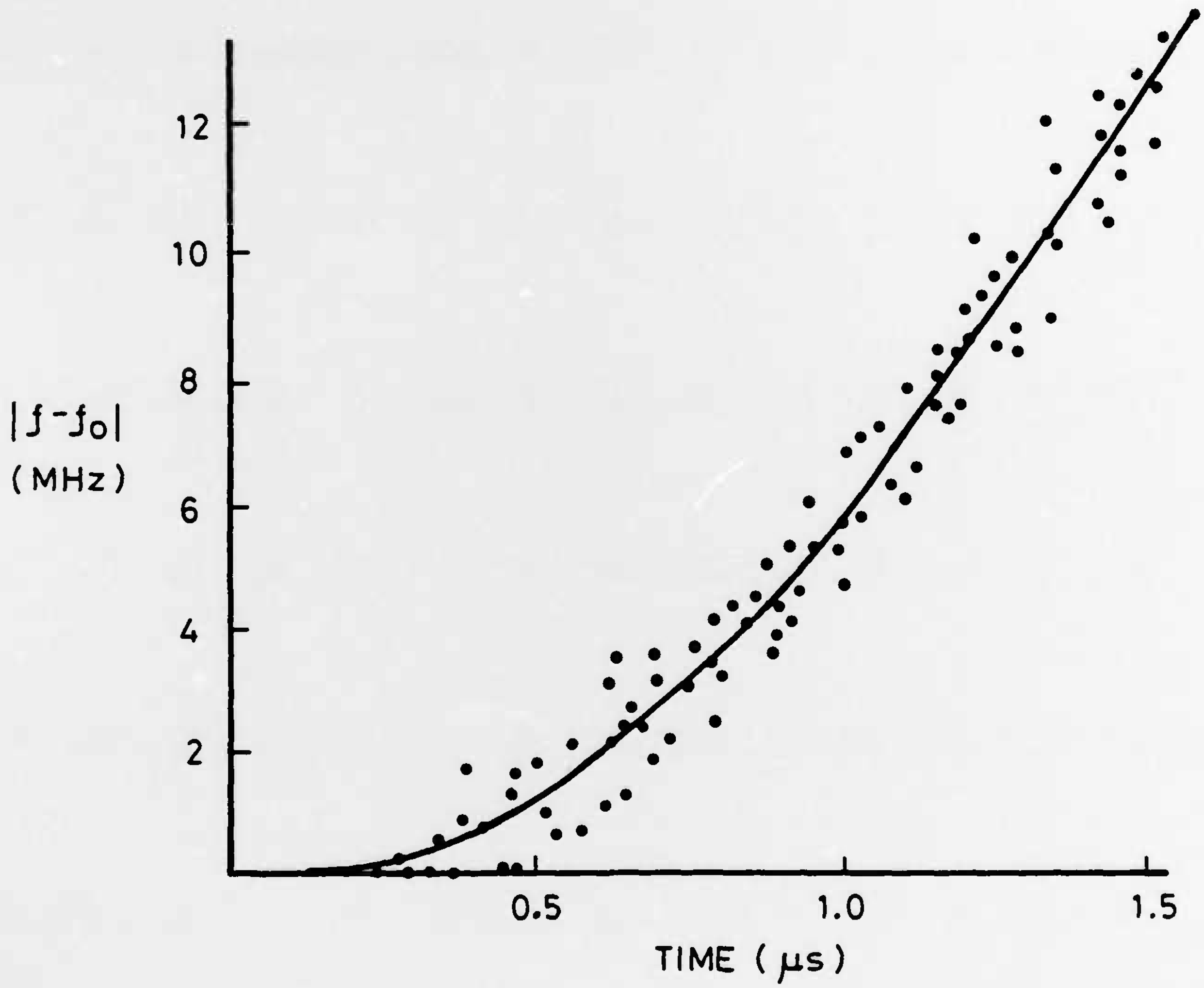

FIG. 5. FREQUENCY CHIRP

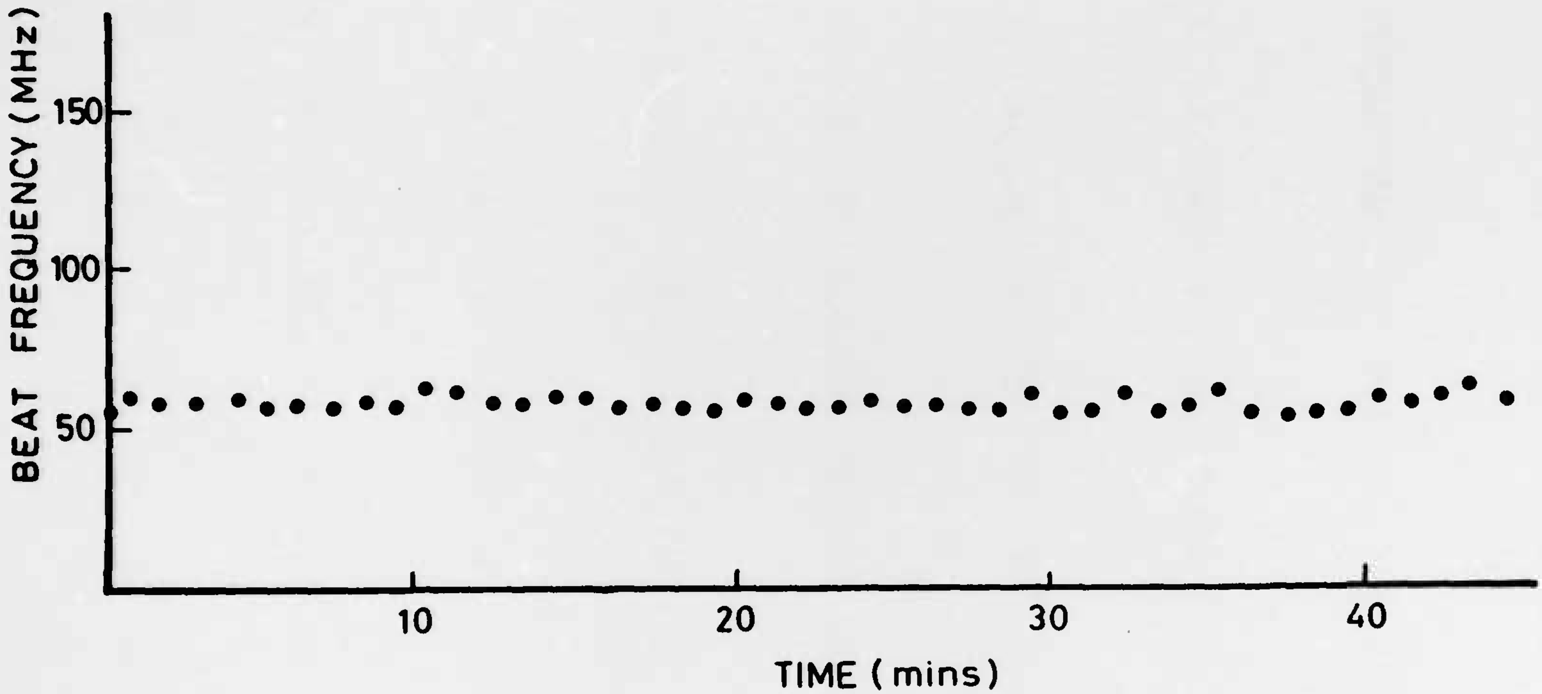

FIG. 6. SHOT - TO - SHOT FREQUENCY STABILITY

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5. Originator's Code (if known)	6. Originator (Corporate Author) Name and Location ROYAL SIGNALS AND RADAR ESTABLISHMENT		
5a. Sponsoring Agency's Code (if known)	6a. Sponsoring Agency (Contract Authority) Name and Location		

7. Title

A COMPACT FREQUENCY - STABLE PULSED CO_2 LASER

7a. Title in Foreign Language (in the case of translations)

7b. Presented at (for conference papers) Title, place and date of conference

8. Author 1 Surname, initials	9(a) Author 2	9(b) Authors 3,4...	10. Date	pp. ref.
JORDAN, D L	HOLLINS, R C			

11. Contract Number	12. Period	13. Project	14. Other Reference

15. Distribution statement
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Descriptors (or keywords)

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Abstract

The aim of this memorandum is to outline the results of work carried out at RSRE to develop a compact frequency-stable CO_2 laser. This work has resulted in the production of a simple, highly compact device (165 x 80 x 50 mm) having a 1.5 MW, 35 ns output pulse which is both inter and intra-pulse frequency-stable to within 3 MHz.